

## Beam energy compensation of a bunch train

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### I. Introduction

When an electron bunch passes through AWA beamline, which consists of a 1.5 cell RF gun and a Linac tank, it will absorb RF energy from the gun and Linac. This causes the stored energy in the gun and Linac to drop down. For the case of single bunch, it is not a problem. However, for a bunch train with very short bunch interval, the declined stored energy in the gun and Linac can not be restored swiftly, so that succeeding bunches experience weaker accelerating gradient, this results in various beam energy for different bunches. In this study we try to find a solution to compensate beam energy drop in a bunch train.

### II. Principle of beam energy compensation

It is known that beam energy absorbed from RF cavities relates to accelerating gradient and initial RF phase when electron beam gets into the cavities. So if we adjust the initial RF phase for each bunch in a bunch train, it is possible to compensate the beam energy drop caused by the reduced accelerating gradient.

Now we return back to our AWA beamline, which consists of a RF gun and a Linac, and try to find some relations between beam energy gain and accelerating gradient and initial RF phase.

#### 1. RF gun

When electrons enter RF gun, the initial velocity is very low. With more energy being absorbed from gun, electron velocity gets faster and faster, and finally close to light speed. The whole accelerating process is very complex, a simple equation can not be obtained to describe the relation of beam energy gain and gradient and initial RF phase. As an alternative, PARMELA [1] is used to find their relations. Fig. 1 shows the relation of beam energy with RF launch phases. In all the simulations we assume maximum accelerating gradient is 77MV/m. Fig. 2 shows the relation between beam energy and maximum accelerating gradient by assuming RF launch phase is  $50^\circ$ . Obviously this is a linear relation. From the two plots we can easily obtain beam energy absorbed from RF gun for any accelerating gradient and initial RF phase by using numerical calculation.

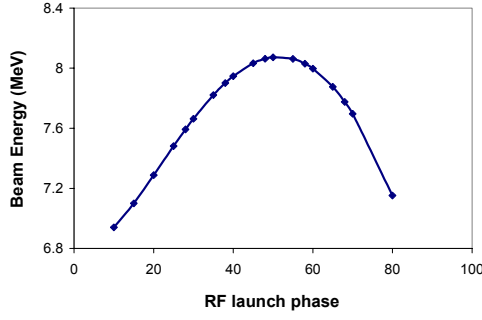


Fig. 1

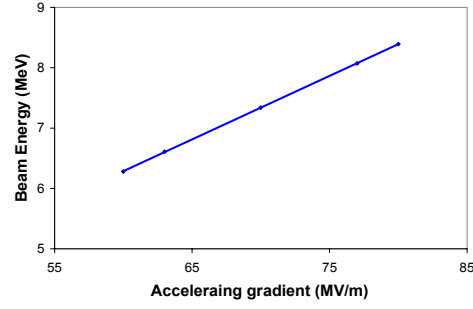


Fig. 2

## 2. Linac

When electron bunch approaches the entrance of Linac, the electron velocity is very close to light speed. For the relativistic beam, beam energy gain has a very simple form [2]:

$$W = q \cdot E \cdot T \cdot L \cdot \sin(\Phi) \quad (1)$$

Where,  $W$  is beam energy gain,  $q$  is bunch charge,  $T$  is transit-time factor, which can be obtained from Superfish simulation [3],  $L$  is Linac length, and  $\Phi$  is initial RF phase when electron bunch arrives at Linac entrance.

Now we have already found relations between beam energy and accelerating gradient and initial RF phase for gun and Linac. In the next step we need to determine accelerating gradient in the gun and Linac. Under the assumption that AWA gun and Linac are critical coupling, we have the following relations:

RF input power ( $P$ ) to gun or Linac is proportional to stored energy ( $U$ ) in gun or Linac,

$$P \propto U \quad (2)$$

Accelerating gradient ( $E$ ) is proportional to square root of stored energy ( $U$ ).

$$E \propto \sqrt{U} \quad (3)$$

By using the relations above, we can obtain accelerating gradient for each bunch in a bunch train. In the next session we will describe how to implement the solution of bunch energy compensation.

## III. Implementation

### 1. Calculation of accelerating gradient for each bunch

From Superfish simulation we can get the following parameters for AWA gun and Linac:

$$P_{N\_gun} = 7219.2276 \text{ W},$$

$$U_{N\_gun} = 0.0229517 \text{ J},$$

$$P_{N\_linac} = 96.5878 \text{ kW},$$

$$U_{N\_linac} = 0.1993215 \text{ J},$$

$$T = 0.786547,$$

Where

$P_{N\_gun}$  is normalized dissipated RF power in AWA gun when assuming electric field

$$E_N = 1 \text{ MV/m},$$

$U_{N\_gun}$  is normalized stored energy in gun when  $E_N = 1 \text{ MV/m}$ ,

$P_{N\_linac}$  is normalized dissipated RF power in Linac when  $E_N = 1 \text{ MV/m}$ ,

$U_{N\_linac}$  is normalized stored energy in Linac when  $E_N = 1 \text{ MV/m}$ ,

T is transit-time factor of Linac.

If we use symbols  $P_{0\_gun}$  and  $P_{0\_linac}$  to express the input RF power to gun and Linac, and assume critical coupling, the initial stored energy and accelerating gradient before first electron bunch enters gun and Linac can be calculated by the equations below:

$$U_{0\_gun} = \frac{P_{0\_gun}}{P_{N\_gun}} \times U_{N\_gun} \quad (4)$$

$$E_{0\_gun} = E_N \times \sqrt{\frac{U_{0\_gun}}{U_{N\_gun}}} \quad (5)$$

$$U_{0\_linac} = \frac{P_{0\_linac}}{P_{N\_linac}} \times U_{N\_linac} \quad (6)$$

$$E_{0\_linac} = E_N \times \sqrt{\frac{U_{0\_linac}}{U_{N\_linac}}} \quad (7)$$

After the first bunch passes through gun and Linac, part of stored energy in gun and Linac is taken away by the bunch. The following equations show how to calculate the declined accelerating gradient in gun and Linac experienced by succeeding bunches. Here we assume that no RF power is pumped into the gun and Linac during the period that the whole bunch train passes through AWA beamline, since the transit time of the whole bunch train is very short and negligible, compared to the filling time of AWA gun and Linac.

$$U_k = U_{k-1} - W_{k-1} \quad (k > 1) \quad (8)$$

$$E_k = E_N \times \sqrt{\frac{U_k}{U_N}} \quad (9)$$

Where

$U_k$  is stored energy in the gun or Linac before bunch k enters,

$W_k$  is beam energy obtained by bunch k from the gun or Linac, whose calculation has been shown in the last session.

$E_k$  is accelerating gradient in the gun or Linac before bunch k enters.

## 2. Calculation of initial RF phase for each bunch

Calculation of initial RF phase plays a key role in our scheme of bunch energy compensation. Initial RF phase for the first bunch should be chosen firstly. From Fig. 1 and Equation (1) in the last session, we found suitable phase range is limited to  $0^\circ - 50^\circ$  for gun and  $0^\circ - 90^\circ$  for Linac, otherwise, the scheme of bunch energy compensation can not be implemented. Due to Schottky effect on photocathode, we prefer to choose a large RF launch phase for high-charge bunches. Another requirement that electron bunches can obtain as more energy as possible from gun and Linac sets another limitation for the selection of initial RF phases. By compromising these requirements we choose the initial RF phase equal to  $30^\circ$  for gun and  $50^\circ$  for Linac.

After having chosen initial phases for the first bunch, the next step is to determine initial phases for succeeding bunches so that beam energy for all the bunches are same. Before discussing this issue, we must clarify two things listed below firstly.

- 1) Since the positions of gun and Linac in AWA beamline are fixed, the initial RF phases that the succeeding bunches get into gun and Linac can not be chosen independently, that is, if the initial phase for gun is decided, the initial phase for Linac is also decided correspondingly.
- 2) For different accelerating gradient and RF launch phase in the gun, the electron transport time from photocathode to the Linac entrance will change. So a corrected phase factor should be added to the corresponding initial Linac phase for each bunch. We apply PARMELA to obtain the relation of transport time with accelerating gradient and RF launch phase, as shown in Fig. 3.

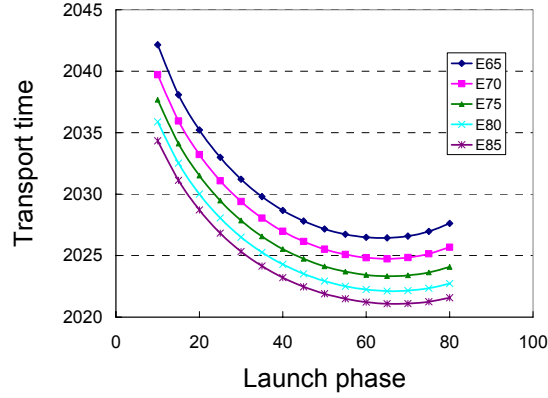


Fig. 3

Now we go back to decide initial phases for the succeeding bunches. For the second bunch, the accelerating gradient in the gun and Linac can be calculated according to the method described above. We can apply the method “Guess and Try” to determine the initial phases. The detailed procedure is described below. Firstly we set the initial gun phase which equals to the initial gun phase of the first bunch plus a small phase step (i.e.  $0.01^\circ$ ) and the initial Linac phase which equals to the initial Linac phase of the first bunch plus same phase step and a corrected phase factor, then one beam energy can be calculated. The energy is compared to the one of the first bunch. Here we set a criterion (i.e.  $0.01\text{MeV}$ ), if the energy difference of the two bunches is larger than the criterion, a larger phase need to be set, a new calculation will be executed. The process will be repeated for many cycles; finally equivalent beam energy can be obtained. Till now does the process of beam energy compensation end. The obtained final phases are the initial phases for the second bunch. By the same way, the initial phases for succeeding bunches can also be obtained.

### 3. Results

In this sub-session we show some results of beam energy compensation for a bunch train. The RF input power to gun equals to  $13\text{MW}$ , RF power to Linac is  $11\text{MW}$ , the initial phases for the first bunch to get into AWA gun and Linac are  $30^\circ$  and  $50^\circ$ , and the charge for each bunch is  $50\text{nC}$ . After the process of beam energy compensation, only 17 bunches can be perfectly compensated, and the beam energy for each bunch is  $16.1\text{ MeV}$  as shown in Fig. 4. Fig. 4 also shows the comparison of beam energy for compensated bunches and uncompensated ones. Fig. 5 shows the variations of stored energy in AWA gun and Linac, Fig. 6 shows initial phase setting of each bunch for AWA gun and Linac.

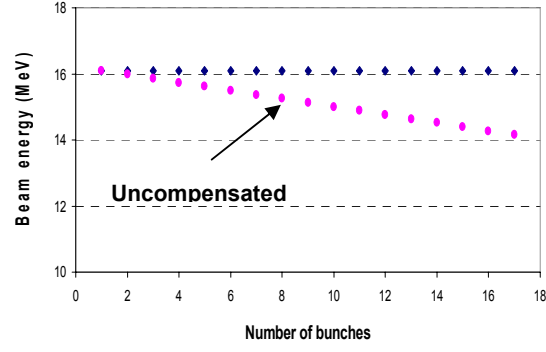


Fig. 4

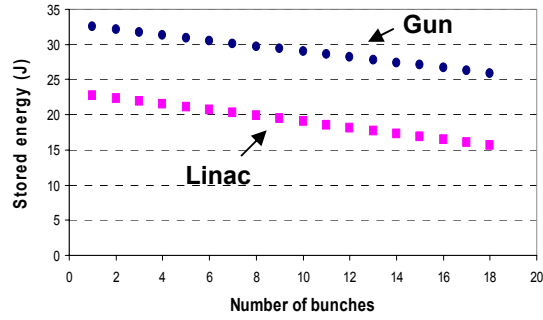


Fig. 5

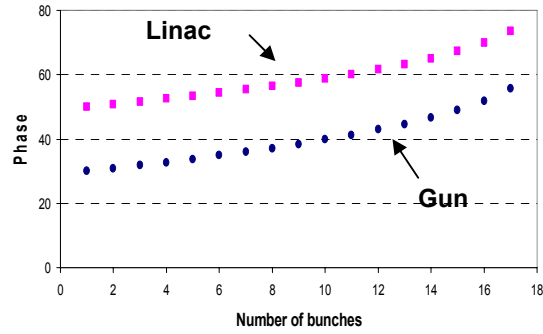


Fig. 6

#### IV. Discussion

##### 1. Limitations of maximum bunch number

The number of bunches that can be compensated is limited by some factors. The first one is the dependency of initial phases of the gun and Linac. Since the positions of the gun and Linac in AWA beamline are fixed, we can not adjust the phases independently, even though there is a phase corrected factor due to various electron transport time for different RF launch phase. As shown in Fig. 1, beam energy reaches maximum when the gun launch phase equals to  $50^\circ$ . Beyond this phase the total beam energy can not be compensated although succeeding bunches obtain more energy from the

Linac. Fig. 6 shows some results for the last bunch, the initial gun phase is  $55.6^\circ$  and corresponding Linac phase equals to  $73.6^\circ$ .

If a smaller RF gun launch phase is chosen as the initial phase for the first bunch, more bunches can be compensated, but we prefer higher RF launch phase for high-charge bunches. This also limits maximum compensable bunch number.

## 2. Comparison of beam quality for first and last bunches

Since accelerating gradient and initial RF phases are different for different bunches, this results in the variations of beam quality for each bunch. Here PARMELA is used to simulate beam evolutions for the first and last bunch in a bunch train; the solenoid fields have been carefully adjusted to minimize the variations of beam quality for these two cases. Some PARMELA input parameters are listed in Table 1. Fig. 8 shows the comparison of beam quality for the two cases, (a) beam energy, (b) normalized rms. emittance, (c) rms. beam envelop, (d) energy spread, and (e) rms. bunch length.

Table 1

	Bunch 1	Bunch 17
<b>E<sub>gun</sub></b>	80MV/m	71.9MV/m
<b><math>\Phi_{\text{gun}}</math></b>	$30^\circ$	$55.6^\circ$
<b>E<sub>linac</sub></b>	10.67MV/m	8.98MV/m
<b><math>\Phi_{\text{linac}}</math></b>	$50^\circ$	$73.6^\circ$

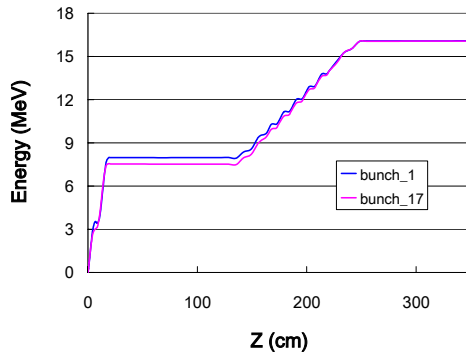
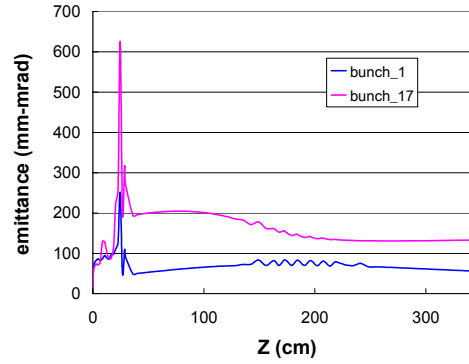
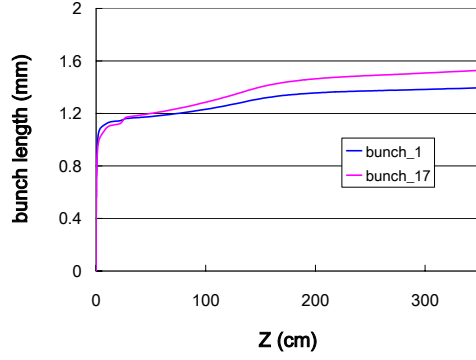


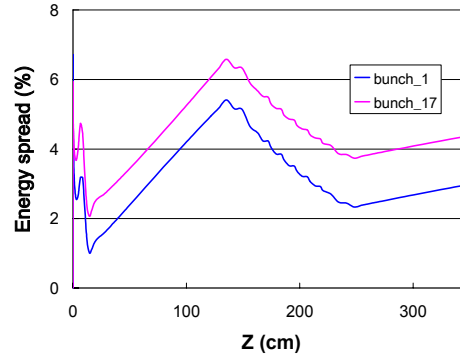
Fig. 8 (a)



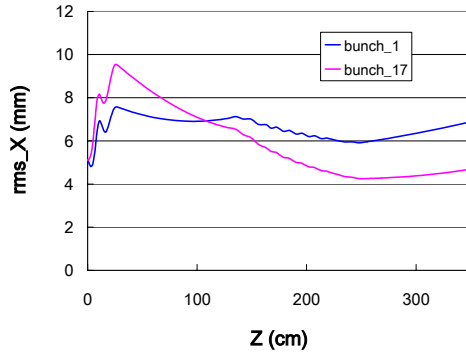
(b)



(c)



(d)



(e)

## V. Summary

When a bunch train pass through AWA beamline, the foregoing bunches absorb part of stored energy in AWA gun and Linac, this results in the declining of accelerating gradient in the gun and Linac, and finally beam energy for the succeeding bunches will come down. To compensate this effect, RF phases that each bunch gets into the gun and Linac, are carefully adjusted to increase beam energy of the succeeding bunches. From Fig. 4 we found this scheme of beam energy compensation is successful. Seventeen bunches with bunch charge equal to 50nC can be compensated; the output beam energy for each bunch is 16.1MeV.

## References

- [1] PARMELA, Los Alamos National Lab, LA-UR-96-1835
- [2] Poisson Superfish, Los Alamos National Lab, LA-UR-96-1834
- [3] T. Wangler, "RF Linear Accelerators", Wiley